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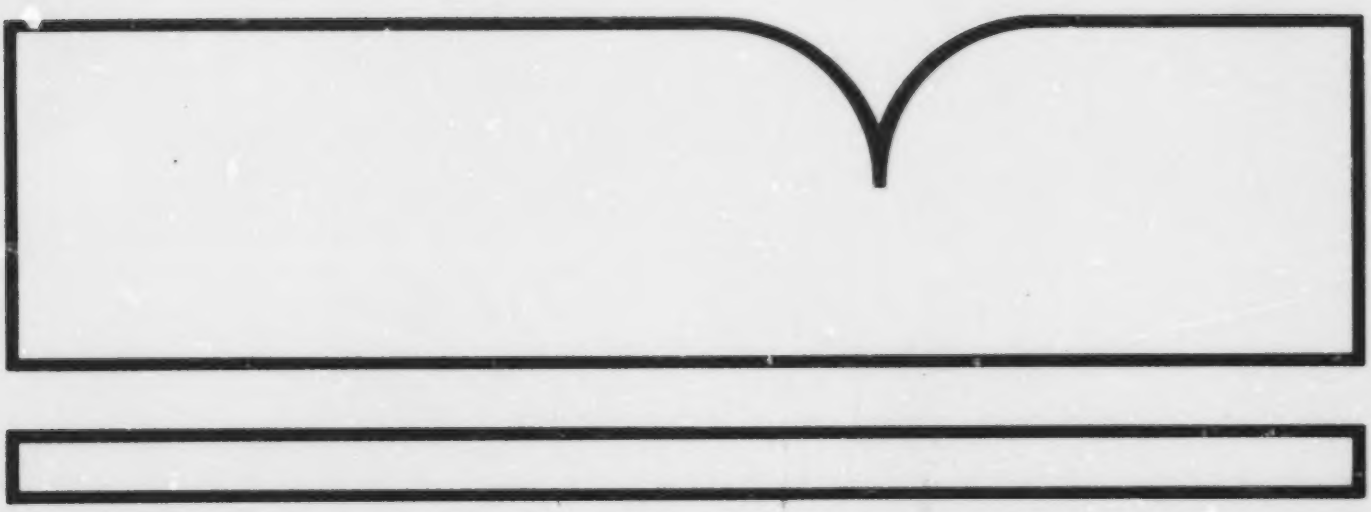

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16. ABSTRACT

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METHODOLOGY FOR DESIGNING AIR QUALITY MONITORING NETWORKS: I. THEORETICAL ASPECTS

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Abstract. An objective methodology is presented for determining the number and disposition of ambient air quality stations in a monitoring network for the primary purpose of compliance with air quality standards. The methodolgy utilizes a data base with real or simulated data from an air quality dispersion model for application with a two-step process for ascertaining the optimal monitoring network. In the first step, the air quality patterns in the data base are collapsed into a single composite pattern through a figure-of-merit (FOM) concept. The most desirable locations are ranked and identified using the resultant FOM fields. In the second step the network configuration is determined on the basis of the concept of spheres of influence (SOI) developed from cutoff values of spatial correlation coefficients between potential monitoring sites and adjacent locations. The minimum number of required stations is then determined by deletion of lower-ranked stations whose SOIs overlap. The criteria can be set to provide coverage of less than some fixed, user-provided percentage of the coverage of tha SOIs of the higher ranked stations and for some desired level of minimum detection capability of concentration fluctuations.

The methodology is applied in a companion paper (McElroy *et al.*, 1986) to the Las Vegas, Nevada, metropolitan area for the pollutant carbon monoxide.

1. Introduction

The Clean Air Act requires state and local agencies to monitor ambient air quality, primarily for documenting an area's compliance with the National Ambient Air Quality Standards (NAAQS). Additional monitoring may be required to satisfy secondary objectives such as providing background or baseline concentrations. Currently, the determination of the number and location of monitoring stations required in a network is primarily based on subjective considerations; semiquantitative rules supported by experience; or sometimes, limited use of analytical tools such as simple Gaussian models (Ludwig and Kealoha, 1975). Nontechnical considerations, such as convenience and accessibility, are usually the dominant factors in selecting a specific monitoring location within the area of interest. On the other hand, because of the fluctuations in pollutant emission rates and the turbulent nature of the atmosphere, pollutant concentration

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distributions are highly variable, both in time and space. The concentrations measured at any given site depend on the emission patterns as well as the atmospheric conditions. The design of an optimal monitoring network, therefore, requires a priori knowledge of these concentration variabilities. An objective methodology for designing such a monitoring network is proposed in this paper.

In a companion paper (McElroy *et al.*, 1983), the methodology is applied as a demonstration to the Las Vegas, Nevada, metropolitan area for the pollutant carbon monoxide. A general outline of the methodology as applied to exposure assessment was previously presented by Richitt *et al.* (1982).

The primary objective of most air quality monitoring programs is to ascertain compliance with air quality standards. That situation, which is considered here, requires that pollutant monitors be located at places where local relative maxima in pollutant concentrations are likely to occur. A technique to determine the number and disposition of such stations should be sufficiently general for application to chemically reactive as well as inert pollutants, multiple pollutants, multiple source configurations (such as a city), and both short-term (e.g., hours) and long-term (e.g., annual) averaging times. It also should be capable of being applied to areas with little or no existing air quality monitoring data in addition to areas with established monitoring networks.

The problem of network design has received a considerable amount of attention. Some techniques have been developed for other objectives such as trends analysis (e.g., Munn, 1981). Others require the use of extensive monitoring data from an existing network (e.g., Buell, 1975; Gether and Seip, 1979; Gustafson and Kortanek, 1973, 1976; and Lee *et al.*, 1978). Some techniques, as currently formulated, are applicable only to long-term annual pollutant concentrations (e.g., Hougland, 1979; Lee *et al.*, 1978; and Nakamori *et al.*, 1979). Some have been developed for use with single-source pollutant emissions (e.g., Noll *et al.*, 1977) and hence would require generalization for use in an urban area with multiple sources. Finally, some techniques use Gaussian models for data base development and hence are not applicable for chemically reactive pollutants (e.g., Hougland, 1979; Noll *et al.*, 1977; and Smith and Egan, 1979) or have not been generalized for application with such pollutants (e.g., Vukovich *et al.*, 1978). The procedure of Koda and Seinfeld (1978) is probably sufficently general but involves the use of a computer algorithm for network selection which appears to be too costly for practical application.

2. Outline of Methodology

An objective methodology is presented for determining the optimum number and disposition of ambient air quality stations in a monitoring network. The proposed methodology uses climatological information and an air quality simulation model. First, the climatological information is used to generate a limited number of meteorological scenarios representative of the region of interest. For each of the scenarios, the air quality simulation model is employed to produce the corresponding temporally varying air quality patterns. The air quality patterns serve as the primary data base in a two-step

procedure for determining the optimal monitoring network. In the first step, the air quality patterns are collapsed into a single composite pattern through the use of the figure-of-merit (FOM) concept. For a specific time interval and location, the FOM is determined as the sum over the meteorological scenarios of the products of the pollutant concentrations and the associated probabilities of occurrence. The resultant FOM fields are used to identify and rank the most desirable monitoring locations. In the second step, the network configuration is determined on the basis of the concept of a sphere of influence (SOI). The SOIs are dictated by a cutoff value in the spatial correlation coefficients between the pollutant concentrations at the monitoring locations identified and the corresponding concentrations at neighboring locations in the region. This cutoff value is statistically related to an estimate of concentration variations that can be accounted for by a given monitoring station. The minimum number of monitoring stations required is then determined by deleting lower-ranked stations whose SOIs overlap the SOIs of higher-ranked stations and whose SOIs provide non-overlapping coverage of less than some fixed percentage of the coverage of the SOIs of the higher-ranked stations. These two steps are discussed in detail in the following sections.

3. Step 1: Identification and Ranking of Potential Monitoring Sites

The first step of the objective methodology for the design of an optimum air quality monitoring network includes the procedures for the identification and ranking of potential monitoring locations. As discussed in prior studies, the desirability of placing an air quality monitor at a given location is closely related to specific monitoring objectives (Ludwig and Kealoha, 1975; Ott, 1975; Liu *et al.*, 1977; and Ludwig *et al.*, 1976). In general, the primary objective of an air quality monitoring network is to monitor the highest concentrations in the area of interest to ensure compliance with air quality standards. These monitoring sites are labeled by Ott (1975) as the 'A'-type stations and by Ludwig *et al.* (1976) as the 'street canyon' and 'traffic corridor' stations for inert pollutants. In addition to this primary objective, secondary objectives for air quality monitoring also exist. For example, as discussed by Ott and Ludwig *et al.*, additional stations may be needed either to measure the population exposure in a residential area or to provide the background as baseline concentrations typical of the outlying rural areas. The former, called the 'C'-type stations by Ott and the 'neighborhood' stations by Ludwig *et al.*, would require additional information, such as demographic data. The latter, called the 'E'-type stations by Ott and 'regional' stations by Ludwig *et al.*, can, however, be incorporated into the present siting algorithm, which is designed primarily for locating the pollutant concentration maxima.

In an earlier study by McElroy *et al.* (1978), the desirability of placing an air quality monitor at a given location in an urban area was determined using the FOM concept. In its most general form, the FOM can be defined as the sum over an exhaustive or comprehensive set of meteorological conditions of the products of an air quality index,

either observed or predicted, and the associated probability of occurrence:

$$\text{FOM} = \sum (\text{Air Quality Index}) \cdot (\text{Probability of Occurrence}) . \tag{1}$$

The summation is to be performed over all meteorological scenarios potentially leading to high air pollutant concentrations. The FOM contains weighting by the probabilities of occurrence of scenarios to avoid situations related to extremely rare events or periods. These situations would not necessarily provide the best criteria for determining a permanent or semipermanent site for a monitoring network.

The air quality index in Equation (1) can be a composite of several pollutant concentrations, again weighted by the relative importance of the individual species, if it is desirable to design a multiple pollutant species monitoring network. For example, to locate a site for measuring multiple pollutant species, the air quality index in Equation (1) can be generalized using a composite concentration index proposed by Ott and Thom (1976):

$$I = \sum_{l=1}^{N} W_l C_l , \tag{2}$$

where I denotes the overall air quality index, C_l is the concentration of species l, and W_l is the corresponding weighting factor reflecting the importance of pollutant species l in the assessment of the overall air quality. In general, C_l can be either an observed or predicted concentration. For the sake of simplicity, only one pollutant species is considered in the present study. In this case, the FOM at any location can be defined as the sum of the products of the concentration of a specific pollutant and the associated probability of occurrence of the corresponding meteorological scenario, which are in turn based on available local climatological data:

$$\text{FOM}(x, y) = \sum_{k=1}^{M} \begin{bmatrix} \text{Concentration at location} \\ (x, y) \text{ under meteorogical} \\ \text{pattern } k \end{bmatrix} \cdot \begin{bmatrix} \text{Probability} \\ \text{of} \\ \text{meteorological} \\ \text{pattern } k \end{bmatrix} . \tag{3}$$

As an alternative, with special emphasis on the detection of maximum concentrations exceeding the NAAQS, the FOM can be defined as a step function of the pollutant concentration in a similar manner:

$$\text{FOM}(x, y) = \sum_{k=1}^{M} \begin{bmatrix} 1, \text{ if NAAQS or some} \\ \text{fraction thereof is} \\ \text{exceeded at location} \\ (x, y) \text{ under meteor-} \\ \text{ological pattern } k; \\ 0, \text{ if not.} \end{bmatrix} \cdot \begin{bmatrix} \text{Probability} \\ \text{of meteorological} \\ \text{pattern } k \end{bmatrix} . \tag{4}$$

in Equations (3) and (4), the pollutant concentration can be either observed or expected. In the present study, the concentration fields are generated from an air quality simulation model, which plays a central role in the siting methodology by linking the known emission distribution with air quality patterns for a given meteorological scenario. The simulated temporally varying air quality patterns, when combined with the corresponding frequency-of-occurrence statistics, permit the determination of the FOM as per Equations (3) and (4).

A selection of the most favorable air quality monitoring sites can be accomplished by ascertaining the noncontiguous peaks in the FOM field and quantitatively ranking locations. This proces, which can easily be carried out nummerically, essentially completes the first step of the siting methodology.

After the identification of the maxima in the FOM field and their ranking according to the corresponding FOM values, two issues remain to be resolved before the optimum monitoring network can be developed. The first issue is related to the representativeness of the air quality data for a selected monitoring station and the establishment of an area surrounding this station for which the data can be extrapolated. The second issue is concerned with the minimum number of measurement stations needed to obtain sufficient monitoring coverage, as determined by the capability of the monitoring network to detect concentration fluctuations. These two issues, apparently interrelated, are addressed in the next section.

4. Step 2: Determination of Spheres of Influence and the Optimum Monitoring Network

The determination of the minimum number of monitoring stations required appears to be the most crucial element in developing an optimum air quality monitoring network. Intimately related to this element is the determination of the spatial coverage, or the sphere of influence (SOI), for each of the monitoring stations. In this context, the SOI is defined as the surrounding area over which the air quality data for a given station can be considered to be representative, or extrapolated with known confidence.

Obviously, the specification of an SOI for any selected site is not unique. Its establishment depends on the method of reconstructing, either through interpolation or extrapolation, the concentration field from the data obtained for a given site. It is conceivable that different interpolation/extrapolation or weighting methods can yield different SOIs, if the interpolation/extrapolation error is kept to a minimum. For example, a linear interpolation might yield a SOI different from an inverse distance extrapolation. In the former case, gradients are assumed to be constant and can be positive or negative. In the latter case, the gradients are not spatially constant and are generally negative, that is, as one progress outward, the extrapolated values decrease monotonically. In an earlier study, an intuitive approach based on the geometry of the computed FOM field was proposed (Liu and Moore, 1980).

A more rigorous approach is adopted in the present study. This approach is based on the statistical properties of the spatial distributions of the pollutant concentrations

used in the first step of the siting methodology. Analogous to the study of turbulence in an Eulerian framework, a spatial correlation coefficient (r) is introduced between values of pollutant concentration at a given site and the corresponding values at its neighboring points as a function of radial distance away from the station:

$$r(s_0, s_0 + \Delta s) = \frac{\text{cov}[C(s_0), C(s_0 + \Delta s)]}{(\text{var}[C(s_0)])^{1/2} \cdot (\text{var}[C(s_0 + \Delta s)])^{1/2}}, \tag{5}$$

where $C(s_0)$ and $C(s_0 + \Delta s)$ can be measured or predicted concentrations at the points s_0 and $s_0 + \Delta s$, and where $\Delta s = [(\Delta x)^2 + (\Delta y)^2]^{1/2}$. The symbols cov and var denote covariance and, variance, respectively, of the arguments. Statistically, the correlation coefficient provides a measure of the intensity of association between $C(s_0)$ and $C(s_0 + \Delta s)$, namely, the concentration at the monitoring sites and its relevance at the neighboring points. This coefficient, lying between -1 and $+1$, thus by itself furnishes an ideal dimensionless tool for the determination of the SOI. Like the correlation coefficient commonly used in the study of turbulent velocity, temperature, and concentration fluctuations, the spatial correlation coefficient is expected to initially decrease from one as the distance increases. Consequently, a cutoff distance of s_c can be found to determine the SOI for a predetermined minimum spatial correlation coefficient as is illustrated in Figure 1.

Thus, in the second step of this siting methodology, the spatial correlation coefficients surrounding each of the potential monitoring sites are evaluated. The computation can

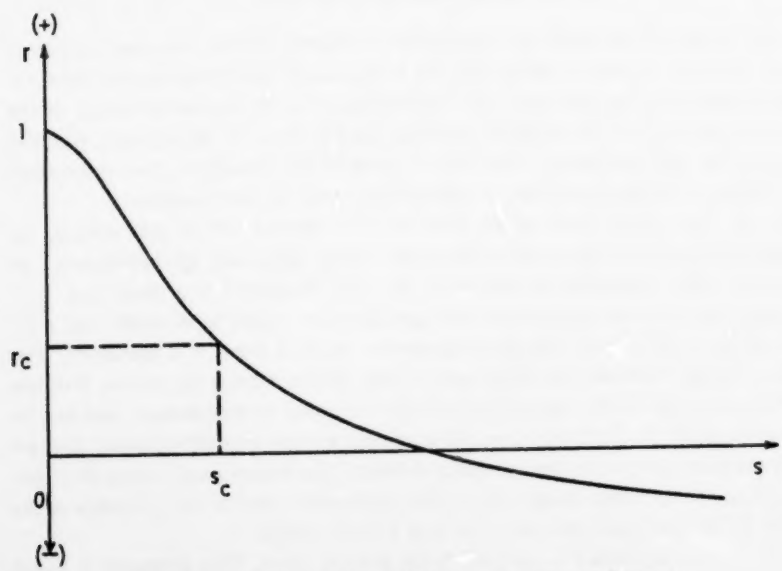

Fig. 1. Generalized correlation coefficient as a function of distance.

be carried out along all radial directions until the spatial correlation coefficient falls below a predetermined minimum or cutoff value. Consequently, the SOI for each stations identified in the first step of the methodology can be determined.

The choice of the cutoff value for the spatial correlation coefficient can be determined statistically for a given monitoring site. Assume that $C_1 = (C_{11}, C_{12}, \ldots C_{1n})$ and $C_2 = (C_{21}, C_{22}, \ldots C_{2n})$ denote the pollutant concentrations at the monitoring site and the corresponding pollutant concentrations at a neighboring point, respectively. A computational form of Equation (5) for C_1 and C_2 with a sample size n is given by

$$r = \frac{\sum_{i=1}^{n} (C_{1i} - \overline{C_1})(C_{2i} - \overline{C_2})}{\sqrt{\sum_{i=1}^{n} (C_{1i} - \overline{C_1})^2 \cdot \sum_{i=1}^{n} (C_{2i} - \overline{C_2})^2}}, \tag{6}$$

where

$$\overline{C_1} = \frac{1}{n} \sum_{i=1}^{n} C_{1i}$$

and

$$\overline{C_2} = \frac{1}{n} \sum_{i=2}^{n} C_{2i}.$$

Assuming that C_1 and C_2 are two correlated random variables from a bivariate normal distribution, a general expression can be derived for the probability distribution of a correlation coefficient, r, associated with a sample size, n, randomly drawn from an infinite population with a true correlation coefficient ρ. This probability distribution p is derived by David (1938) as follows:

$$p(r \mid n, p) = \frac{(1 - \rho^2)^{n-1}}{\pi(n-3)!} (1 - r^2)^{(n-4)/2} \frac{d^{n-2}}{d(\rho r)^{n-2}} \frac{\arccos(-\rho r)}{\sqrt{1 - (\rho r)^2}} \tag{7}$$

The probability integral, E, given by

$$E = \int_{r_1}^{r_2} p(r \mid n, \rho_0)\, dr, \tag{8}$$

then represents the confidence level of the test hypothesis that $r = \rho_0$ with $r_1 < \rho < r_2$ as the confidence interval.

The probability integral, Equation (8), can be evaluated using a quadrature method (David, 1938). In Figure 2, the confidence interval for correlation coefficients at a 95 percent confidence level are reproduced from *Tables of the Ordinates and Probability Integral of the Distribution of the Correlation Coefficient in Small Samples* (David, 1938).

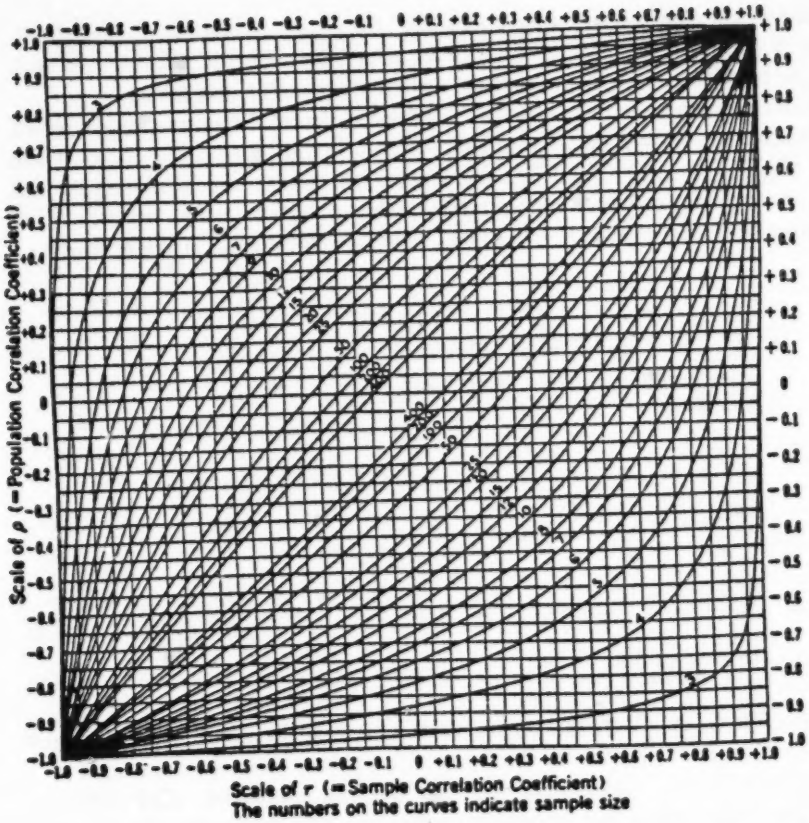
Scale of ρ (= Population Correlation Coefficient)
Scale of r (= Sample Correlation Coefficient)
The numbers on the curves indicate sample size

Fig. 2 Confidence interval (belts) for the correlation coefficient at 95% confidence level. (This figure is reproduced with permission of E. S. Pearson, from David (1938). Cambridge University Press for the Biometrika Trustees).

If a linear relationship is assumed between the variables, then the square of the correlation coefficient represents the fraction of the variance of which C_2 can be accounted for by the variations in C_1 (Ezekiel, 1941). Note that the use of r_2 or ρ^2 in this way does not imply a causal relationship between C_1 and C_2 but that a linear association exists between them such that $100\,\rho^2$ is the percentage of concentration variations explained by concentration variations at a potential monitoring site. Thus,

$$\text{variance explained} = \rho_c^2 \quad . \tag{9}$$

Once the minimum desired value of variance explained is selected, the minimum acceptable value of ρ_c can be determined from relationship (9). This value for ρ_c can be entered into a nomograph such as Figure 2 as a lower bound to obtain a cutoff value for the sample coefficient, r_c, for a specific sample size. The SOI for each of the ranked

stations can then be established:

$$A_1 = A(x_1, y_1)$$

$$A_2 = A(x_2, y_2)$$

$$A_3 = A(x_3, y_3)$$

$$\ldots,$$

$$A_N = A(x_N, y_N)$$

where A_i, $1 \leq i \leq N$, is defined by all points (x, y) that lie in the simply connected region containing station (x_i, y_i) enclosed by a contour determined by $r > r_c$. The total areal coverage by the monitoring network for all N stations, as illustrated in Figure 3, is given by

$$A_{\text{Network}} = A_1 \cup A_2 \cup A_3 \cup \ldots \cup A_N. \tag{10}$$

The determination of the minimum number of monitoring stations required can be then

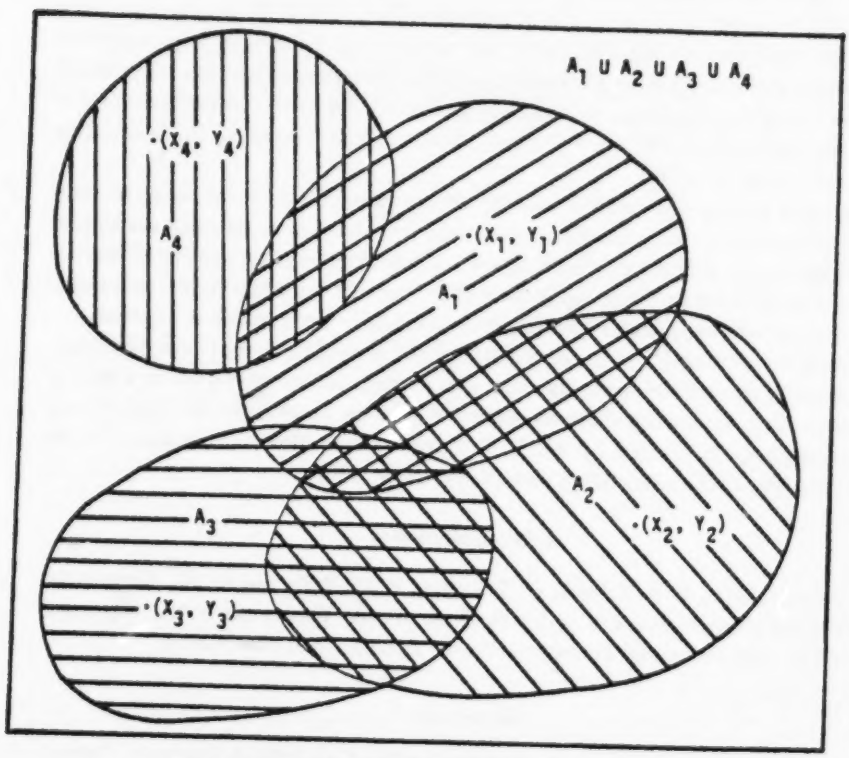

Fig. 3. Joint areal coverage for multiple monitoring stations.

carried out by deleting lower ranking stations whose SOIs overlap the SOIs of the higher ranking stations and whose SOIs provide non-overlapping coverage of less than some fixed percentage of the coverage of the higher ranking stations.

5. Discussion and Concluding Remarks

It should be noted that our proposed methodology may not yield an optimum solution in a rigorous mathematical sense. That is, the derivative of an objective function subject to specified constraints is not maximized or minimized. However, the proposed procedure attempts to achieve the same goal, in a heuristic but pragmatic manner in that it searches out maximum values of a well-defined function in an object. The geographical locations of these values are then prioritized in an objective and systematic fashion in descending order as potential monitoring sites.

Our proposed methodology considers only in situ monitoring at fixed locations. With the rapid advances in instrumentation hardware, particularly in remote or long-path sensing devices, other candidates are emerging as potential platforms for measurements. They include individuals (personal monitors), vehicles, aircraft, and satellites. At best, such platforms currently serve only a complementary role in air quality monitoring programs. It is possible that, because of their mobility, these platforms may outperform conventional fixed stations in the future. At that time, and as regulations are modified to permit their more routine use, a trade-off analysis based on the cost-effectiveness of different monitoring modes will likely become an indispensable part in the optimization of a monitoring network.

The utility of the proposed methodology is by no means limited to the design of a new monitoring network. It should also prove useful for modification (through addition or relocation, for instance) of an existing network that has known or suspected deficiencies. It can also be used to locate monitoring sites that accommodate future anticipated emission distribution patterns resulting from projected urban growth or renewal.

Finally, a data base should be developed to permit the evaluation and intercomparison of alternative network design techniques. This perhaps can be carried out in a fashion similar to that accomplished for air quality simulation models via the Regional Air Pollution Study sponsored by the U.S. Environmental Protection Agency in the St. Louis, Missouri, metropolitan area (Schiermeier, 1978).

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